Agriculture, Ecosystems and Environment 184 (2014) 124–134

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Mitigation of phosphorus leaching losses via subsurface drains from a cracking marine clay soil

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ARTICLE INFO

Article history:
Received 24 June 2013
Received in revised form
11 November 2013
Accepted 19 November 2013
Available online 20 December 2013

Keywords:
Mitigation
Cracking soil
Particulate phosphorus
Preferential flow
Subsurface leaching

ABSTRACT

In Scandinavia, subsurface transport via tile drains contributes significantly to phosphorus (P) and nitrogen (N) leaching from arable land, which adds to the eutrophication of surface waters. Using flow-proportional water sampling, various options for mitigating subsurface P leaching losses (and N leaching) were examined in 28 experimental plots on a flat, tile-drained site with 60% marine clay. Two crop rotations and unfertilised fallow were monitored for a total of six years. In addition to topsoil management practices (different forms of tillage, structural liming and mineral P fertilisation), local spatial variations in subsurface transport were determined within the experimental area.

Mean total P (TotP) leaching losses after conventional autumn ploughing and inverting the soil to a depth of 23 cm were 0.79 kg ha^{-1} year^{-1}, with 87% occurring as particulate P (PP), and the corresponding mean total N leaching losses were 27 kg ha^{-1} year^{-1}, with 91% occurring as nitrate. The coefficient of variation in TotP leaching both in spring before the experiment started (64%) and during the six-year experiment (60%) was higher than the coefficient of variation in P-soil status (20%), or drainage (25%), illustrating the importance of local-scale subsurface transport in this cracking clay. However, TotP and PP leaching losses were significantly ($p_r > F < 0.002$) lower from plots with structural liming than from the other treatments grouped together. Different P fertilisation strategies (band-spreading/broadcasting of mineral P and applying a balanced amount/no P fertiliser) had no significant effect on P leaching losses. Nitrogen leaching was significantly ($p_r > F < 0.001$) lower from unfertilised fallow than from other treatments and was not significantly lower after shallow autumn tillage than after conventionally ploughing, whereas PP losses tended to be higher. Infiltration measurements with tension infiltrometers revealed a high variation in saturated hydraulic conductivity within plots. In view of the generally high PP losses, efforts to combat eutrophication of the nearby Baltic Sea should concentrate on soil structure improvements, while extensive tillage and totally omitting P fertilisation of cracking soils with moderate soil P status appears to be inefficient mitigation options.

1. Introduction

Mobilisation and transport of phosphorus (P) from terrestrial systems to streams and rivers cause eutrophication and deteriorating water quality. Excessive and unbalanced nutrient concentrations in surface waters and eutrophication problems were first recognised in the mid-20th century (Redfield, 1958). Carpenter (2008, citing Schindler, 1977) and Smith (1983) pointed out the necessity of reducing the nitrogen (N) load simultaneously with the phosphorus (P) load in order to avoid enhancing eutrophication further. The current high P load to the Baltic Sea is having an exceedingly negative impact on this brackish and sensitive water body (Boesch et al., 2006) which is something that needs to be urgently addressed. The P load from agricultural soils can be considerable, especially from cracking clays (Ulén and Persson, 1999; Uusitalo et al., 2001) and erosion-prone silts (Lundekvam and Skøien, 1998).

In northern and north-western Europe, a large proportion of arable land has tile drainage, e.g. 30% in the UK and 40% in Denmark (Brown and van Beinum, 2009). In Sweden 1.1 million ha arable land (41% of total arable land) are artificially drained (Wesström, 2002) and most of them are clayey soils. Tile drainage of heavy clay, a dominant soil type in eastern Sweden and south-western Finland, is especially common. Tile drainage systems can serve as transport pathways directly from agricultural land to streams

Abbreviations: P–AL, ammonium lactate–extractable soil phosphorus; NO_3–N, nitrate nitrogen; PP, particulate phosphorus; TotN, total nitrogen; TotP, total phosphorus.

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http://dx.doi.org/10.1016/j.agee.2013.11.017

and large subsurface transport of P from agricultural clay soils via tile drains has long been reported (e.g. Bolton et al., 1981; Bottcher et al., 1981; Grant et al., 1996). Enhanced amounts of exchangeable soil-P in preferential flow areas in topsoils and fast (non-equilibrium) transport have been demonstrated by Sinaj et al. (2002). With such flows, which can be highly irregular in time and space (Jarvis, 2007), P leaching may be greater than predicted by the classical convection–dispersion equation (Stamm et al., 1998). Via further transport through tile drainage systems (Øygarden et al., 1997), in Sweden typically draining into a ditch and with recommended drain spacing ranging from 10 to 24 m (SBA, 1996), surface-generated P from agricultural land can effectively reach watercourses, lakes and seas.

Great efforts have been made to evaluate the effectiveness of measures against P transport losses by water, which are often employed in combination with measures to reduce N leaching (e.g. Cherry et al., 2008; Newell Price et al., 2011). One potential improvement strategy is to modify the fertiliser-spreading technique. When fertiliser is band-spread (placement of fertiliser using a coulter) as opposed to broadcasting at a similar application rate, the fertilised crop grows faster and yield is increased, especially in crops with large inter-row spacing and/or restricted root distribution (Schoumans et al., 2014). Depending on the crop, the recommended amount of P can be reduced to moderate levels when P is band-spread and the risk of incidental losses of dissolved reactive P (DRP) after fertilisation is reduced. Furthermore, with reduced fertilisation levels the likelihood of long-term P accumulation and P leaching losses may be lower than with broadcasting.

In shallow tillage, usually referred to as reduced tillage, the soil is not inverted and is only tilled to a depth of 5–15 cm with a cultivator, disc harrow or rotovator. This leaves the soil surface covered with at least 15% of crop residues year-round, according to the US definition (ASAE, 2006). However, this may cause enrichment of P and organic material in the uppermost topsoil and increase the risk of P losses, including leaching via tile drains (Gaynor and Findlay, 1995). In contrast, conventional ploughing can disrupt macropores and reduce hydraulic conductivity at tillage depth and consequently decrease losses of P. The advantage of regular ploughing in order to reduce DRP transport has been demonstrated e.g. in a five-year study of a Finnish clay soil (Koskiaho et al., 2002). However, in the same study, erosion and nitrogen losses were reduced with shallow tillage compared to ploughing. In another five-year study on a Finnish clay soil, both DRP and particulate P (PP) losses were lower with conventional ploughing than with shallow tillage (Uusitalo et al., 2007). For soils where preferential flow and transport are important, regular ploughing is generally considered to interrupt continuous macropores and to reduce pesticide leaching (Isensee et al., 1990).

Preferential flow has been shown to be the dominant transport pathway for different pesticides from a cracking clay soil in Sweden (Ulén et al., 2013), with the five pesticides studied showing similar leaching patterns irrespective of sorption strength. There was a large spatial variation in pesticide leaching between field plots, despite a moderate variation in water discharge. During major flow events and with water-saturated topsoil, the concentration of dispersed clay is known to be high in drainage water and the concentration of dissolved P is low at moderate-low soil P status (Ulén and Persson, 1999). There is an urgent need for improved technologies for long-term stabilisation of this soil type and mitigation of accompanying preferential flows. Incorporation of quicklime (structural lime in the form of calcium oxide, CaO) into the topsoil is a measure which immediately improves the soil structure. When lime is added to clay soil, cation exchange takes place and calcium ions are adsorbed on clay minerals, the clay particles are then attracted closer to each other and flocculation and particle aggregation occur (Bell, 1996). In addition, pozzolanic reactions between lime, silica and alumina lead to the formation of cementing products and long-term increase in soil strength (Locat et al., 1990). At the site used in the present study, a significant improvement in soil aggregate strength has been demonstrated after structural liming, evaluated as a reduction in readily dispersed clay in a laboratory test (Ulén et al., 2012a). Since P is known to be strongly adsorbed to clay particles, reduced transport of P should follow. After structural liming, clay colloids in the topsoil are also known to form a 'card-house' pattern (e.g. Wells and Theng, 1988). This re-arrangement of the clay colloids may influence the uniformity of water flow in time and space, in turn altering the pre-conditions for preferential transport of P.

The aim of this study was to quantify leaching losses of P (and N) from a tile-drained cracking soil under two crop rotations over a six-year period in relation to topsoil management practices. We also wanted to investigate possible spatial variation in P leaching, based on the spatial gradient in pesticide leaching found by Ulén et al. (2013) at this field. Our starting hypotheses were that: (i) P leaching losses are reduced for several years after structural liming; (ii) shallow tillage does not reduce P leaching losses in comparison with regular ploughing; and (iii) application of moderate amounts of P mineral fertiliser close to balance does not increase P leaching compared with no P fertilisation. As an extension of hypothesis (iii), band-spreading was compared with broadcasting of P fertiliser.

2. Materials and methods

2.1. Experimental site

An experimental field (1.3 ha) with a subsurface drainage water collection system was used for the study. The site, which comprises 28 plots, was constructed in 2006 on a flat (mean slope less than 0.05‰) clay soil of marine origin in eastern Sweden. The plots are situated in two rows of 14 at varying distances from an open ditch that acts as the recipient for drainage water from the surrounding valley (Fig. 1). In order to match the experimental plots to farm machinery, plot dimensions are 20 m × 24 m (0.048 ha) and the drains are placed centrally, with 8 m spacing (Fig. 1), in order to drain the soil effectively.

Composite soil samples were taken from all plots in autumn 2007, after harvest but before tillage and before the different treatments started. Composite samples were taken at three depths in each plot: 0–23 cm (the plough layer), 23–60 cm and 60–90 cm. Composite soil samples were also taken from all plots in spring 2012 (one month before fertilising and cultivation), but only the uppermost topsoil (0–2 cm) was sampled at that time. Some general physical and chemical properties of the soil are described in detail by Ulén et al. (2013). The soil has high clay content (60%), with minor spatial variation in both topsoil and subsoil, and the dominant clay mineral is illite. At greater depth the bulk density is low and the organic matter is low in nitrogen. Just before the experiment started, in autumn 2007, the mean topsoil (Ap horizon, 0–23 cm) organic carbon content (Table 1) was 2.5%, with a coefficient of variation of less than 17% between all plots, while the mean plant-available P content in the topsoil, analysed after extraction with acid ammonium-lactate solution (P–AL) (Egnér et al., 1960), was 32 mg kg^{-1} (coefficient of variation 20%). This very moderate value corresponds to the second lowest of six classes (I, II, III, IVa, IVb and V) used in Sweden to assess the need for P fertilisation and the risk of P leaching. In another study at the site in 2011, a similar topsoil (0–30 cm) P–AL value (38 mg kg^{-1}) (recalculated from kg P–AL ha^{-1}) was measured close to the ditch (Andersson et al., 2013). This was equivalent to 17 mg kg^{-1} Olsen-P (Olsen et al., 1954). Total P content (mean 827 mg kg^{-1}) analysed after oxidative acid combustion with nitric acid is typical for Sweden in general

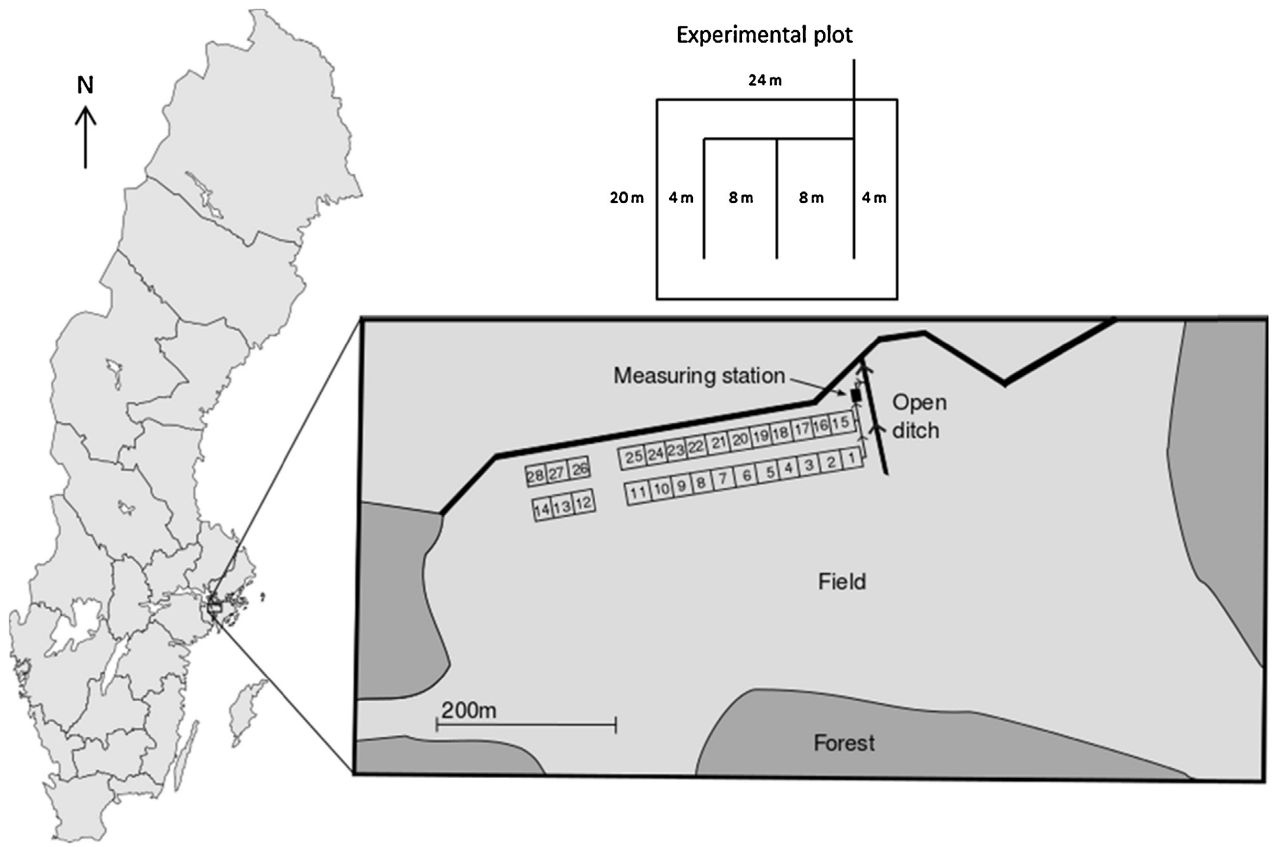

Fig. 1. Map of Sweden and location of the experimental site with 28 drained plots and the recipient ditch in the centre of the flat valley. Water sampling took place in a measuring basement situated close to the NE corner of plot 15.

Table 1
Mean values of soil pH (H_2O) and concentrations of organic carbon (OC, %), ammonium-lactate phosphorus (P–AL, mg kg^{-1}) and total phosphorus digested with HNO_3 (TotP, mg kg^{-1}) in the different treatments. Maximum standard deviations (SD) within treatments are given. Soils were sampled at the start of the experiment in autumn 2007 and in spring 2012. Note the different sampling depths in 2007 and 2012.

Treatment code	2007 (0–23 cm depth)				2012 (0–2 cm depth)			
	pH	OC	P–AL	TotP	pH	OC	P–AL	TotP
A—Conventional ploughing, placement P	6.4	2.4	47	830	6.1	2.8	47	880
B—Conventional ploughing, no P	6.4	2.6	54	760	6.1	3.1	40	790
C—Conventional ploughing, liming[a], placement P	6.3	2.5	52	830	6.6	3.0	45	880
D—Shallow tillage, placement P	6.5	2.4	43	800	6.3	3.0	50	860
E—Shallow tillage, broadcast P	6.4	2.5	49	830	6.1	3.1	61	910
F—Unfertilised fallow[b]	6.6	2.4	46	760	6.1	2.9	31[**]	770
G—Adapted crop rotation[c]	6.4	2.5	50	780	6.1	3.1	50	870
Max SD within treatments	0.5	0.3	8	nd	0.4	0.5	10	80

[a] Structural lime treatment in autumn 2007.
[b] Sown with barley in spring 2008.
[c] Autumn sown crops broadcast fertilised in spring, otherwise placement of P in spring.
[**] Significantly lower ($p < 0.5$) than in all other treatments.
nd = no data, in 2007 TotP was only measured in two out of four plots, within each treatment.

(Eriksson et al., 2013). Mole-based P saturation is low (5%) and the P sorption index (PSI_2) is high (7.3 μmol kg^{-1} soil) (Ulén et al., 2012a). Thus the soil generally has a high ability to sorb P.

Variation in pesticide leaching between different plots is large at the current site, despite small variation in water discharge (Ulén et al., 2013). The distance from the mid-point of the plots to the receiving ditch (located at the bottom of the flat valley, see Fig. 1) can be used as a factor of the spatial variation in transport, since Ulén et al. (2013) found a clear relationship between the ranking of plots according to pesticide concentration in drainage water and distance to the ditch. Leaching of the surface-applied pesticides followed the same pattern as PP.

2.2. Soil management and crop rotations

During a balancing year after the experiment was initiated, water discharge showed a moderate coefficient of variation (26%) for the different drained plots, while TotP leaching showed a high coefficient of variation (64%) (Table 2). Three soil management practices (four replicates per treatment) were randomly assigned to 20 plots: conventional autumn ploughing (treatments A and B), structural liming (treatment C) and shallow autumn tillage (treatments D, E) (Table 1). Treatment A represented the usual practice for the region, with conventional mouldboard ploughing inverting the soil to 23 cm depth in autumn before spring sowing and application of the recommended P fertiliser dose. In treatment B,

Table 2
Treatment code, discharge (mm), leaching losses (kg ha^{-1}) of total phosphorus (TotP) and coefficient of variation (CV) (%) between the four replicate plots and between all treatments and all plots in spring 2007, before the experiment started.

Treatment	Discharge		TotP	
Code	Mean	CV	Mean	CV
A	90	7	0.073	48
B	103	13	0.078	44
C	85	12	0.085	70
D	80	11	0.055	25
E	98	14	0.063	11
F	95	23	0.062	6
G	77	6	0.042	7
All treatments	89	10	0.065	22
All plots	89	26	0.065	64

the plots were autumn-ploughed as usual, but P fertilisation of the spring-sown crop was completely omitted. In treatment C, quicklime was applied in dry conditions to stubble in four plots in 2007 at a rate of 5 t (CaO) ha^{-1} and incorporated immediately into the soil by a cultivator driven in different directions. In the following years (2008–2012), these plots were conventionally ploughed. For treatments D and E, 8 plots were shallow-tilled (to 12 cm depth) twice in all years and reconsolidated with a rib-roller in 2010–2012. Broadcasting of P fertiliser (treatment E) was compared with band-placement (treatment D) in these shallow-tilled plots. Broadcasting also took place in treatment G when fertilising winter crops in spring.

In order to repeat the autumn tillage treatments, the crops in the main experiment (treatments A–E) were grown in a rotation with annual spring sowing (rotation I) (Table 3). Crop rotation II (treatment G) comprised a more varied crop rotation which is typical for the region and included winter wheat. In three years of crop rotation II (2010–2012), treatment G was autumn-ploughed simultaneously with treatments A–C. For reference, unfertilised fallow was sown in spring 2008 (treatment F) and the grass vegetation was cut yearly as fallow and not removed. With the aim of reducing N leaching, in 2012 oilseed radish was sown in treatments A and B soon after harvest (8 August). However, due to an early frost this crop was frozen by mid-October and the residues were ploughed under on 15 November.

All P fertilisation doses were just slightly above the level expected to be removed by the following crop (Table 4). Only mineral fertilisers were used in the experiment and both N and P (superphosphate) fertilisers were applied each year in connection to sowing (Table 4). In treatment G, autumn sown crops were broadcast fertilised in spring at the same time as the fertilisation of the other treatments, while spring sown crops were fertilised in connection with sowing by band placement (except for treatment E which was also broadcasted). All plots except the fallow treatment were regularly treated with pesticides when needed (Ulén et al., 2013) and wild oats removed by hand.

2.3. Soil porosity, water-holding capacity and water infiltration

Topsoil samples (8 replicates) from treatments A (conventional ploughing), C (structural liming) and F (unfertilised fallow), sampled in April 2011 before spring cultivation, were analysed in the laboratory for pore volume and dry bulk density (Danielson and Sutherland, 1986). The volume of soil pores was roughly estimated as the difference between water content at 5 cm tension pressure and the initial water content. Water-holding capacity was measured as water content at different tensions in small core samples (0–5 cm) in the laboratory (Messing and Jarvis, 1993). On 27–30 June 2011, water infiltration was measured in the field for treatments A and C (in total three plots, each with three measurements) using a tension infiltrometer with supply heads of −10, −8, −4.5, −2 and −1 m as described by Holden et al. (2001).

2.4. Precipitation, water sampling and analysis

Precipitation was measured at the site with tilting bucket equipment and collected in a data logger. Since snow amounts are easily underestimated with this equipment, the snow cover was recorded manually (5 days a week) on an open field at the Norsborg drinking water treatment plant, situated 6 km north-east of the experimental site. Snow accumulation between melting periods was estimated from this data. Water discharge from each plot was measured with tilting vessels in an underground basement and the water volume was related to the area of each plot. Automatic sampling of drainage water also took place in the basement, guided by a data logger. This controlled the flow-proportional sampling in the basement of the station by means of small tube pumps, with each flow-proportional subsample representing 0.003 mm discharge in summer and 0.04 mm discharge the rest of the year. After a certain volume of water had passed, the suction tube was first cleaned by reverse pumping and thereafter a small volume was sampled. The composite water samples were collected in dark glass vessels (2.5 L) at relatively cold temperature (approximately 10–14 °C) and in darkness for a maximum of one week, prior to the transport of smaller flasks to the laboratory for chemical analysis. From every plot a 100 mL sample was taken in a glass bottle for P analysis and a 100 mL sample in a plastic bottle for pH and N analysis.

The 100 mL water samples were immediately sent to the Water Laboratory (Department of Soil and Environment, SLU), where pH was measured the following day, dissolved reactive P (DRP) within two days and total P (TotP), nitrate nitrogen (NO_3–N) and total nitrogen (TotN) within 4 days after storage at +4 °C. Total P was analysed as soluble molybdate-reactive P after acid oxidation with $K_2S_2O_8$ (ECS, 1996). Dissolved

Table 3
Year, treatment code (A–F), crop and date of main soil tillage in crop rotations I and II and plots/total number of plots. 16 plots (A, B, C and G) were conventionally ploughed, 8 plots (D–E) were simultaneously shallow-tilled and 4 plots (F) were unfertilised fallow after a balancing year with winter wheat followed by autumn tillage.

Year	Rotation I (A–E)	Conv. tillage (16/20 plots)	Rotation II G	Conv. tillage (4/4 plots)	Unf. fallow F	Tillage (4/4 plots)
2007	Winter wheat	25 Sept-07	Winter wheat	25 Sept-07	Winter wheat	25 Sep-07
2008	Spring barley	23 Sept-08	Winter wheat	23 Sept-08	Barley+insow	–
2009	Spring barley	13 Oct-09	Winter wheat	13 Oct-09	Unfert. fallow	–
2010	Oats	14 Oct-10	Oats	14 Oct-10	Unfert. fallow	–
2011	Pea	28 Oct-11	Pea	28 Oct-11	Unfert. fallow	–
2012	Spring barley[a]	15 Nov-12	Spring barley[b]	15 Nov-12	Unfert. fallow	–

[a] Oil radish sown after harvest 9 August 2012.
[b] Field cress insown.

Table 4
Date of sowing and fertilisation, fertilisation rates (Fert) (only mineral fertiliser used), phosphorus and nitrogen removal by the crop (C remov) and leaching (Leach) (kg ha^{-1} $year^{-1}$) for different treatments (A–G), crops and years. Mean value of yearly soil balance is presented. In addition, the soil balance excluding 2011 (when the main pea crop was eaten by birds) is shown.

Year	A	B	C	D	E	G	A	B	C	D	E	G
	Phosphorus						Nitrogen					
2008	Spring barley (9 May-08)					*Ww*[a]	Spring barley					*Ww*[a]
Fert.	20	–	20	20	20	24	90	90	90	90	90	120
C remov	13	12	15	14	12	15	89	84	95	81	82	84
Leach	0.7	0.8	0.4	0.8	0.9	0.6	24	29	24	23	24	22
2009	Spring barley (8 May-09)					*Ww*[a]	Spring barley					*Ww*[a]
Fert.	18	–	18	18	18	13	90	90	90	90	90	120
C remov	15	14	15	14	14	19	106	97	118	92	84	106
Leach	0.4	0.8	0.6	0.9	1.1	0.6	19	20	25	12	13	12
2010	Oats (17 May-10)						Oats					
Fert.	20	–	20	20	20	20	100	100	100	100	100	100
C remov	15	14	15	12	13	13	78	71	75	59	66	68
Leach	0.5	0.5	0.4	0.8	0.9	0.5	25	21	27	16	20	18
2011	Pea (10 May-11)						Pea					
Fert.	20	–	20	20	20	20	0	0	0	0	0	20
C remov	0	0	0	0	0	0	0	0	0	0	0	0
Leach	0.7	0.9	0.5	0.8	0.9	0.6	23	17	22	13	20	17
2012	Spring barley (24 May-12)						Spring barley					
Fert.	16	–	16	16	16	16	104	108	104	104	105	104
C remov	12	12	12	12	12	12	74	74	70	73	90	69
Leach	1.1	1.5	0.9	10.	1.2	1.4	52	68	55	33	52	49
	Mean harvested crop						Mean harvested crop					
Fert.	19	–	19	19	19	18	77	78	77	77	77	93
C remov	11	10	11	10	10	12	69	65	72	61	64	65
Leach	0.7	0.9	0.6	0.9	1.0	0.7	29	31	31	19	26	24
Balance	+7	−11	+7	+8	+8	+6	−21	−19	−25	−4	−13	+4
Balance excl. 2011	+4	−14	+4	+5	+5	+3	−21	−19	−26	−1	−12	+4

[a] Winter wheat as crop, sown on 8 Oct-2007 and 25 Sept-2008 and fertilised in spring (9 May-2008 and 8 May-2009).

reactive phosphorus (DRP) was analysed after pre-filtration using filters with a pore diameter of 0.2 μm (Schleicher & Schüll GmbH, Dassel, Germany). Particulate P (PP) was estimated as the difference between TotP and DRP. Total nitrogen (TotN) was analysed with a carbon nitrogen (CN) analyser (Shimadzu, GmBH, Duisburg, Germany). Nitrate–nitrogen and nitrite–nitrogen were analysed together (ISO, 1996) and referred to as 'nitrate–nitrogen (NO_3–N)'.

2.5. Statistical analysis

A general mixed model (SAS software Version 9.2) was used to analyse differences in P and N leaching between the different treatments. Yearly losses from all plots and all years were used in the analysis. To account for the time series str ucture of the data, correlations between measurements over time were modelled with a spatial power covariance structure (Littell et al., 2006). The concentration of several pesticides together with PP in discharge water were demonstrated to decrease with increasing distance from each plot to the open ditch (location demonstrated in Fig. 1) (Ulén et al., 2013). The distance between the plots and the ditch was therefore included in the statistical analysis as a factor of spatial variation in leaching. Interaction effects between treatment and discharge and between treatment and distance to the open ditch were tested. Treatment was used as a fixed factor, while the factors discharge and distance to the open ditch were used as covariates. All variables were logarithmically transformed before the statistical analysis in order to stabilise the variance, which increased with increasing values of transport losses. In the post hoc tests with pairwise comparisons between treatments, the distance was set at an average value of 200 m, and discharge at a median value of 410 mm. Tukey's method was used for multiple testing corrections. A significance level of $\alpha = 0.05$ was used, including the p value associated with the F statistics of a given effect ($p_r > F$).

3. Results and discussion

3.1. Precipitation and drain water discharge

Mean yearly precipitation at this site is 690 mm. During the period studied, it varied normally for the region at between 650 and 760 mm. This (eastern) part of Sweden typically experiences early summer drought, but receives more rain in July. There is usually a high water surplus during the winter, which includes periods of accumulated snow followed by snowmelt in spring or earlier. In the period studied, accumulated snow usually melted in March–April. However, discharge pattern was very different between the different years studied, with two winters hardly having any snow accumulation (2007/2008 and 2008/2009) followed by two winters with unusually high snow accumulation (2009/2010 and 2010/2011) and two years of moderate snow accumulation (2011/2012 and 2012/2013) (Fig. 2a). Early snowmelt periods with substantial drainage volumes occurred in January 2010 and 2012 (Fig. 2b). In June 2012, very intensive early summer rainfall occurred (total 165 mm), followed by 93 mm water discharge. In the 2010 growing season, a relatively dry June was followed by repeated rainstorms of escalating intensity in July/August (total 170 mm), which resulted in high discharge (total 107 mm). August 2012 was also wet, with 128 mm rain followed by 70 mm discharge. Autumn tillage for spring crops usually takes place in October, but in 2012 this month was unusually wet, with a total discharge above 100 mm, so soil cultivation took place at the beginning of November under wet conditions.

Drainage was highly efficient and practically all autumn–winter precipitation (mean 94%) was discharged through the subsurface

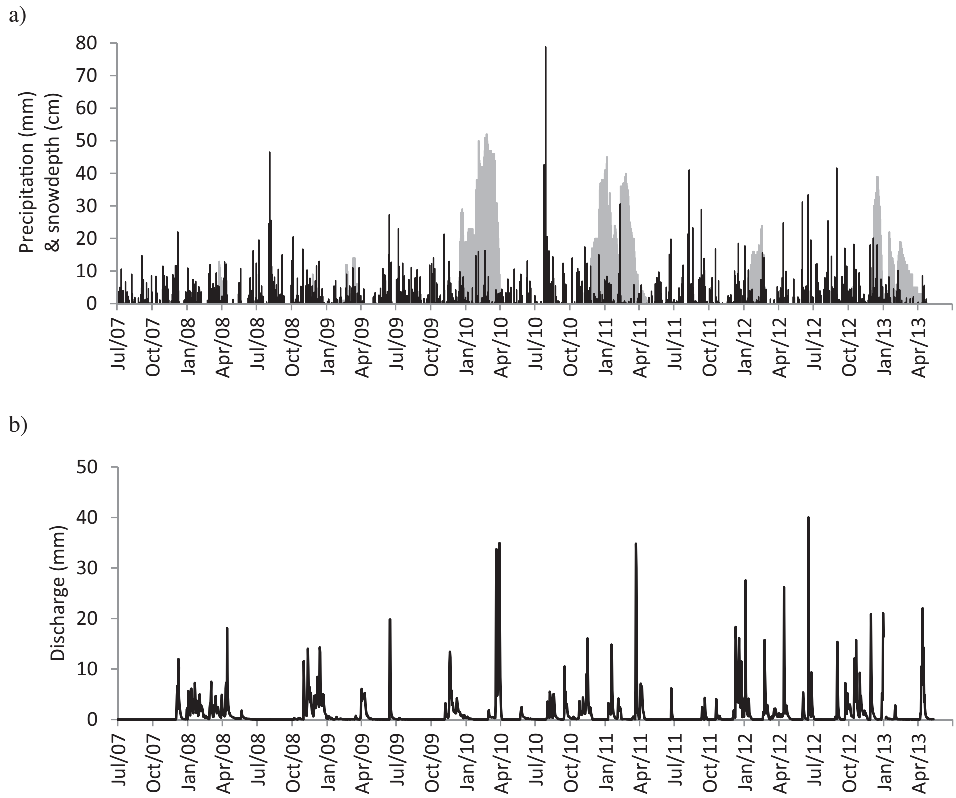

Fig. 2. (a) Precipitation (mm) shown in black and snow cover (cm) shown in grey and (b) daily mean drainage on the experimental field in July 2008–2013.

drains in the period October–April. Water discharge between the different plots had a mean coefficient of variation of 22% in summer and 25% in winter. A yearly variation of around 20–25% between different plots is quite typical in plot experiments (e.g. Monaghan et al., 2002; Strock et al., 2004). The variation in total yearly water discharge between plots was not explained by the distance to the ditch ($p = 0.08$).

3.2. Yield and soil P balance

Winter wheat and barley are the most common cereal crops in the region and these generally produced relatively satisfactory yields of 4–5 t ha^{-1}. However, the yield of oats in 2010 was quite low (around 3 t ha^{-1}), with unfavourable weather conditions (a dry spring and wet ripening season) being an important explanatory factor. Pea, used as a break crop in 2011, was to a large extent eaten by birds. The residues were tilled under in order to let them germinate and act as a catch crop for N the following autumn. Germination and growth of barley in 2012 was problematic due to early spring drought. Omission of P fertilisation (treatment B) reduced the yield significantly ($p < 0.05$) with a mean reduction of 7% for all years and in comparison with treatments (A, C, D and E), while plots with structural liming demonstrated higher yields in the first two years than plots with only conventional ploughing (Table 5). No general effect of shallow tillage on yield was observed.

Soil P balance was slightly positive (Table 4) except in treatment B (no P fertiliser), as the real crop removal of P was smaller than expected. Soil N balance (excluding the year with pea) ranged between −24 and +2 kg ha^{-1} year^{-1}. The P–AL concentration in the upper topsoil (0–2 cm) was significantly lower in the unfertilised fallow than in other treatments, but tended to be highest in the shallow-tilled treatments (D and E) (Table 1). In contrast, there was no significant difference in P–AL between treatments A and B, despite the latter not receiving any P fertiliser for five years.

Table 5
Yield in treatments B–E, representing crop rotation I, relative to treatment A. Mean values exclude 2011, when no yield was removed but pea residues were tilled under in order to germinate as a catch crop for nitrogen.

Year	Rotation I (A–E)	A	B	C	D	E
2007	Winter wheat	100	101	98	101	102
2008	Spring barley	100	94	113	96	100
2009	Spring barley	100	96	107	117	89
2010	Oats	100	91	100	79	88
2011	Pea	–	–	–	–	–
2012	Spring barley	100	89	97	108	103
	Mean	100	92	104	100	95

3.3. Soil porosity, water-holding capacity and hydraulic conductivity

In treatment A, which was ploughed each autumn for a spring crop, the mean porosity of each plot was estimated to be between 0.52 and 0.54 cm^3 cm^{-3} (0–5 cm) in April 2011 (Table 6). Water-holding capacity at four of the five tension pressures tested was significantly higher for fallow (F) than for ploughed plots. Compared with the fallow, the autumn ploughed treatment (A) had only slightly higher porosity (0.53 compared with 0.52 cm^3 cm^{-3}) and a slightly larger pore volume (0.17 compared with 0.14 cm^3 cm^{-3}). These differences were not statistically significant. Field measurements in June 2011 indicated the lowest hydraulic conductivity, close to saturation, in plots with structural liming (C) compared with conventionally ploughed plots (A) (Fig. 3). However, since the spatial variation at high tensions was very large within the plots, this difference was not statistically significant.

3.4. Spatial variation in leaching

Total P leaching was 0.86 kg ha^{-1} year^{-1} as an average for all years and all treatments, with PP being the dominant

Table 6
Mean soil physical properties measured on core samples (0–5 cm depth) in the laboratory. Mean values and standard deviation (SD) of initial soil water content ($cm^3 cm^{-3}$), porosity ($cm^3 cm^{-3}$), dry bulk density ($g cm^{-3}$) and water content ($cm^3 cm^{-3}$) at five different tension pressures (t.p.) (m) and total depleted water ($cm^3 cm^{-3}$) between 0.05 and 6.0 tension pressure (t.p.). Measurements were only made in treatments A, C and F.

Property	A (conventional ploughing)		C (structural liming)		F (unfertilised fallow)	
	Mean	SD	Mean	SD	Mean	SD
Initial water content	0.346	0.028	0.324	0.026	0.359	0.026
Porosity	0.539	0.031	0.525	0.032	0.520	0.014
Dry bulk density	1.18	0.09	1.22	0.08	1.30	0.04
Water content 0.05 t.p.	0.505	0.016	0.495	0.022	0.495	0.010
Water content 0.5 t.p.	0.428	0.018	0.414	0.017	0.458**	0.023
Water content 1.0 t.p.	0.413	0.019	0.399	0.017	0.444**	0.024
Water content 3.0 t.p.	0.388	0.017	0.378	0.016	0.416**	0.024
Water content 6.0 t.p.	0.365	0.017	0.356	0.017	0.395**	0.023

** Significantly different from conventional ploughing ($p < 0.05$).

Table 7
Mixed model analysis on the effects of different factors and factor interactions (only significant for P) on leaching losses of P and N ($kg ha^{-1} year^{-1}$). The factors include treatment (Treat), year, subsurface discharge (SubD); distance to a ditch (Dist) as a factor of spatial variation; and the factor interactions (Treat × SubD; Treat × Dist). The *p*-value associated with the F statistic of a given effect and test statistic is shown in the table.

Main effects and interactions	TotP	PP	DRP	TotN	NO_3–N
Treat	0.0108	0.0731	0.0728	<0.0001	<0.0929
Year	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
SubD	<0.0001	<0.0001	0.0065	<0.0001	<0.0001
Dist	<0.0001	<0.0001	0.9939	0.0013	0.2218
Treat × SubD	0.5387	0.3104	0.1312	0.0007	0.8940
Treat × Dist	0.0037	0.0267	0.0009	0.4621	0.8340

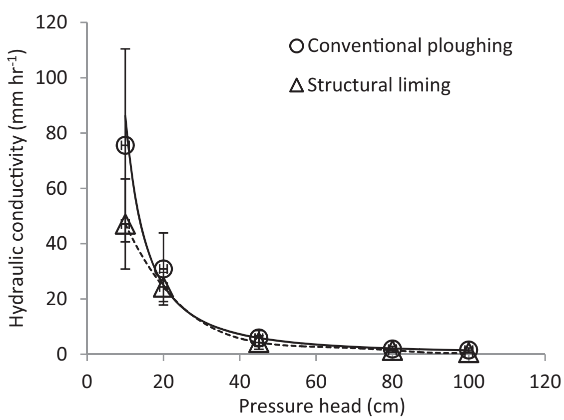

Fig. 3. Geometric mean of saturated hydraulic conductivity from tension infiltration studies in the field on 27–30 June 2011. Measurements in plots with conventional ploughing (A) are compared to measurements in plots with structural liming and conventional ploughing (C). Error bars with standard deviations.

fraction ($0.72 kg ha^{-1} year^{-1}$). Average TotN leaching was $23 kg ha^{-1} year^{-1}$, with NO_3–N being the dominant fraction ($20 kg ha^{-1} year^{-1}$). A greater coefficient of variation in TotP leaching in the spring before the experiment started (64%) than in soil P status (20%) and drainage (26%) (Table 2) indicate the importance of local-scale soil transport pattern for P leaching in this clay soil. No surface runoff was observed within the flat study area during the experimental period. Lateral flows below the soil surface, e.g. on a plough pan, were also unlikely to occur, since there was no distinct plough pan at the site.

As a result of a general large variation in P concentrations in discharging water from different plots, the coefficient of variation in TotP transport between all plots was large (60%) during the experiment, despite a moderate coefficient of variation in water discharge (25% between all plots). The interaction between treatment and distance was significant when TotP and PP leaching losses were dependent variables ($p = 0.004$ and 0.027, respectively) (Table 7), meaning that there was a spatial variation (expressed as a gradient towards the ditch) in P leaching, as well as significant effects of some of the treatments. At the same time, subsurface discharge volumes were not dependent on the distance to the central ditch ($p = 0.08$, data not shown).

Since, surface applied pesticides leached with a similar pattern as PP at this site, topsoil was suggested to be the major source of PP (Ulén et al., 2013). Together with the large spatial variation in P leaching, this indicates that preferential flow was the dominant transport pathway in this clay soil. Our results cannot explain the reason for the gradient in P leaching, but one possibility is that there were more continuous macropores and permanent cracks closer to the ditch. Preferential flow pathways, especially those in direct contact with drains, can serve as effective transport pathways for PP and pesticides (Stamm et al., 1998). Phosphorus leaching might be influenced, directly or indirectly by the local subsoil pH and in the deeper subsoil (60–90 cm), the pH decreased towards the ditch ($R^2 = 78\%$, $p < 0.001$) (Ulén et al., 2013). The presence of gyttja (cohesive old matter of organic origin settled in marine or lake sediment) can strengthen crack walls and turn them into permanent pathways. Such material was indicated as brown and red areas in the soil profile and was more commonly observed closer to the ditch. However, this was not detected as any gradient in organic carbon content in the subsoil.

Topsoil organic carbon content clearly increased with a decrease in distance between the plot and the recipient ditch ($R^2 = 70\%$, $p < 0.001$) (Ulén et al., 2013). Therefore water infiltration into the topsoil may be an additional factor determining the varying conditions for preferential flow, although this could not be verified with measurements at the present site. A significant relationship between leaching and the distance to the ditch was also demonstrated for TotN ($p_r > F = 0.001$) but not for NO_3–N ($p_r > F = 0.22$) (Table 7). The latter may indicate that relatively more NO_3–N might have mobilised from the soil matrix irrespective of any varied

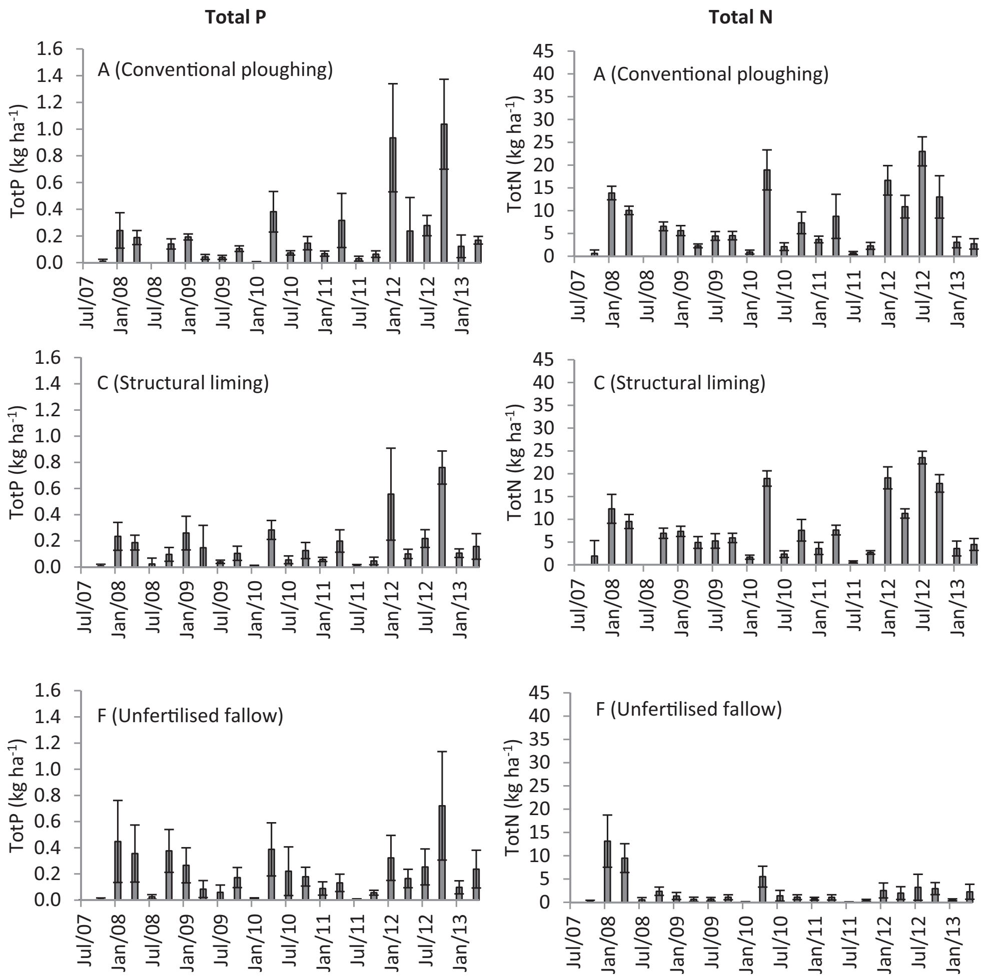

Fig. 4. Seasonal (3 months) leaching losses of total P (TotP) and total N (TotN) in conventionally ploughed plots (A), plots with structural liming (C) and unfertilised fallow (F) (sown with barley in spring 2008 and fully established in 2009). The bars represents the seasons March–May, June–August, September–November and December–February. Error bars with standard deviations.

conditions in the subsoil, in contrast to P which may be mobilised from the very topsoil under wet conditions and may be reaching the drains in areas with intensive macropore flow.

3.5. Temporal variation and seasonal losses of P and N

Losses exceeding 1 kg P ha^{-1} year^{-1} were found in 4–17 plots (15–60% of the experimental area) in different years within the six-year period. Such high losses are generally associated with incidental P losses shortly after application of manure or mineral fertiliser (Withers et al., 2003), but at the study site high P leaching took place all year around, mainly in the form of PP. These high losses did not represent 'worst case' conditions with a rich soil P source shortly after fertilisation, but 'a worst case' of transport with accelerated water flow, which is known to be initiated by wet topsoil conditions (e.g. Kramers et al., 2012) and high precipitation intensity (e.g. Köhne and Horts, 2005). In two of the six years, such conditions occurred during snowmelt. For the conventionally ploughed plots, TotP mean leaching losses were 0.41 kg ha^{-1} in the snowmelt period in 2010 compared with 0.19 kg ha^{-1} in autumn 2009, and 0.30 kg ha^{-1} in the snowmelt period in 2011 compared with 0.20 kg ha^{-1} in autumn 2010. The highest seasonal P leaching losses (>1 kg TotP ha^{-1}) were recorded in September–November 2012 from the conventionally ploughed plots (Fig. 4). This was probably a result of autumn tillage being carried out under wet conditions in that period. TotP losses from the plots with structural liming were lower (Fig. 4), but the difference was proportionally less than in other autumn periods. The general conditions for effective N mineralisation were probably favourable in spring 2012. In May 2012, the NO_3–N concentration in drainage water from all ploughed plots was unusually high (mean 27 mg L^{-1}). Unusually high concentrations were also recorded in drainage water from the unfertilised, non-ploughed fallow (mean 14 mg L^{-1}). This might be a combined effect from high N mineralisation and unusually low denitrification, since high N mineral soil concentrations has been observed in zero-plots from other experiments in the region in that period. The highest N leaching over the entire six-year period for the cultivated plots occurred in summer 2012, with high discharge in June. In that period N leaching from unfertilised fallow was more moderate (Fig. 4).

At the present site with moderate P–AL status, the DRP concentration was generally only 17% of TotP, but increased to 30% in snowmelt periods. As exemplified here for 2010/2011, the measured pH in snowmelt water (after storage in the glass vessel in the basement for up to a week) tended to be lower (6.6) than in the previous autumn (Table 8). Simultaneously, the DRP concentration was twice as high as in the previous autumn. The measured drop in (logarithmically transformed) pH represented 75% more H^+ ions which, in addition to the low electric conductivity in snowmelt water, may have influenced the electrical charge of P and the hydrogen bonds of the minerals. In addition, the relatively low pH may have dissolved some Ca-bound P from the clay particles (Devau

Table 8
Mean discharge (Disch), pH (in stored composite samples) and flow-proportional concentrations of dissolved reactive P (DRP) and particulate P (PP) from plots with different tillage treatments in five periods with high water flow in 2010-2011. Soil tillage took place on 14 October 2010.

Period	22–27 Sept	28 Sept-25 Oct	26 Oct-8 Nov	8–15 Nov	21–28 March
Conventional ploughing (A,B)					
Disch (mm)	8.2	9.2	25.5	33.5	72.9
pH	6.5	7.2	7.0	6.7	6.6
DRP (mg L^{-1})	0.021	0.021	0.018	0.020	0.048
PP (mg L^{-1})	0.132	0.122	0.161	0.168	0.120
Structural liming (C)					
Disch (mm)	10.4	13.5	29.1	30.1	74.4
pH	6.9	7.3	7.2	6.9	6.6
DRP (mg L^{-1})	0.018	0.017	0.015	0.020	0.047
PP (mg L^{-1})	0.075	0.066	0.093	0.100	0.078
Shallow tillage (D,E)					
Disch (mm)	10.8	15.6	25.9	29.7	76.4
pH	6.8	7.2	7.1	6.8	6.6
DRP (mg L^{-1})	0.024	0.024	0.023	0.027	0.047
PP (mg L^{-1})	0.142	0.236	0.411	0.275	0.136

Table 9
Leaching (kg ha^{-1} $year^{-1}$) of total P (TotP), dissolved reactive P (DRP), particulate P (PP), total N (TotN), nitrate N (NO_3–N) and the ratio of total N/total P (N/P) for the different treatments. Mean values of yearly transport from four plots and six years are given with ±standard deviation. Values with different letters within columns denote significant differences between treatments, which was tested for significance with log-transformed values in the mixed model analysis.

Treatment	TotP	PP	DRP	TotN	NO_3–N	N/P
A–Conv. plough.	0.79 ± 0.53	0.68 ± 0.49	0.13 ± 0.09	27^{c} ± 13	25^{b} ± 11	42 ± 21
B–Conv. plough. no P	0.97^{b} ± 0.66	0.82^{b} ± 0.55	0.15 ± 0.11	29^{c} ± 19	26^{b} ± 17	42 ± 28
C–Conv. plough. Lime	0.59^{a} ± 0.33	0.46^{a} ± 0.29	0.13 ± 0.06	30^{c} ± 13	27^{b} ± 11	59 ± 26
D–Shallow till.	0.96 ± 0.56	0.85 ± 0.51	0.11 ± 0.07	18^{b} ± 8.5	15^{b} ± 7.1	25 ± 15
E–Shallow till., broadc. P	1.13^{b} ± 0.51	0.94^{b} ± 0.38	0.20 ± 0.16	$27^{b,c}$ ± 16	23^{b} ± 14	26 ± 17
F–Unfertilised fallow[d]	0.77 ± 0.42	0.60 ± 0.31	0.17 ± 0.16	6.2^{a} ± 3.3	3.3^{a} ± 2.5	8.6 ± 2.8
G–Adapted crop.	0.84^{b} ± 0.48	0.68 ± 0.39	0.16 ± 0.23	$23^{b,c}$ ± 13	19^{b} ± 11	31 ± 17

[d] Period 2008–2013, excluding the year before the unfertilised fallow was established (2007/2008).

et al., 2011). High DRP concentrations in snowmelt are frequently observed for highly charged Swedish clay soils, which commonly contain illite, a dominant mineral at the present site (Ulén, 2003; Ulén & Snäll, 2007).

3.6. *Effects of soil management and fertilisation on P and N leaching*

Mean annual losses in the different treatments are shown in Table 9, together with standard deviations and significant differences between treatments (based on the mixed model analysis). A few significant differences in P and N losses were found between treatments, but losses of TotP and PP from the plots was to a great extent explained by the spatial variation in the experimental field as discussed in Section 3.4. Mean annual losses of Total P and PP in the different treatments were significantly lower from plots with structural liming (C) than from conventionally ploughed plots without P fertiliser (B), and also significantly lower than from shallow tilled plots with broadcasting of P fertiliser (E) (Table 9). Yearly PP losses were on average 0.36 kg ha^{-1} $year^{-1}$ lower (44% reduction) from plots with structural liming (C) than from conventionally ploughed plots without P fertiliser (B), and on average 0.48 kg ha^{-1} $year^{-1}$ lower (51% reduction) from plots with structural liming (C) than from shallow tilled plots with broadcasting of fertiliser P (E). Also, when TotP and PP leaching losses from plots with structural liming (C) were compared to all other treatments grouped together (A, B, D, E and G), P leaching losses were significantly ($p_r > F < 0.002$) lower from plots with structural liming (C). The corresponding reduction in leaching with structural liming was 37% TotP and 42% PP.

The amount of TotP leached from individual plots in treatment A and B varied between 0.24 and 2.28 kg ha^{-1} $year^{-1}$. Tile-drain losses in this range have been reported from Swedish single observation fields with clay soil (Ulén et al., 2012b). No rainfall was recorded shortly after fertilisation (which always took place in spring and in mineral form) and no incidental losses of fertiliser P seemed to occur. This and the moderate soil P concentration may explain the general low DRP/TotP ratio (mean 0.18). No significant differences were found between conventionally ploughed plots with or without P fertilisation (A and B). Placement or broadcast of fertilisers in the shallow-tilled plots (D and E) neither had any clear effect on P leaching (Table 9). Broadcasting fertiliser P may increase soil P concentration in the surface layer, while placement of fertilisers increases soil P below the surface (Saarela and Vourinen, 2010; Fernández and Schaefer, 2012), especially if the soil is not inverted by ploughing. However, in our study the P–AL value in plots with broadcasting (E) compared to plots with placement (D) (Table 1) was not significantly higher. Neither was the (significantly) lower P–AL value of unfertilised fallow in the 0–2 cm layer in 2012 associated with any statistically significant lower DRP leaching in the pairwise comparison of treatments. No significant differences between any treatments were found in DRP leaching in the pairwise comparisons (when distance was set at 200 m and discharge set at 410 mm). At the present site with a moderate soil P status (P–AL = 30–50 mg kg $soil^{-1}$), omitting P fertilisation did not decrease P leaching, but the yields decreased. For other Swedish soils with similar moderate soil P status (P–AL < 50 mg kg $soil^{-1}$) a yield response to P fertilisation has also been demonstrated (Edhe, 2012).

Shallow-tilled plots (treatment D, E) tended to have higher PP leaching than conventionally ploughed plots (treatment A, B), while N losses tended to be lower (Table 9), although not significant. In 2012 the shallow-tilled plots had slightly higher (not statistically significant) P–AL value in the upper topsoil compared to conventional ploughed plots, but there were no differences in DRP leaching. Greater accumulation of P in the surface layer cannot explain the slightly higher P losses, as suggested for conservative tillage in a Canadian study (Gaynor and Findlay, 1995). In their study most losses took place as DRP and a clear difference in DRP leaching was found between zero tillage and conventional ploughing, while in the present case the main difference in leaching took place in the form of PP. A possible explanatory factor for the tendency for higher PP losses could be shallow and uneven accumulation of crop residues in shallow-tilled plots, which might have resulted in uneven infiltration and preferential P transport along straw residues. However, this needs to be investigated further. Additionally, it is unclear from the present results whether the changes in particle organisation after liming (improved aggregate stability and the 'card-house' clay mineral structure) resulted in a more spatially uniform infiltration, thus moderating preferential flow. Careful studies of soil cracks and other types of macropores in the soil under different treatments are needed in order to clarify this. The variation in conditions, in terms of transport pathways through the soil, between plots seems most important. Such factors might have over-shadowed any effects from less effective P mitigation options than structural liming in the present study.

Interaction effects between discharge volume and treatment (the latter the statistically fixed factor) were found to be significant for TotN, but not for NO_3–N, (Table 7), and therefore the statistical results for N leaching are difficult to interpret. However, shallow-tilled plots (treatment D, E) tended to have lower N leaching losses (both TotN and NO_3–N) than other cultivation treatments. Nitrogen leaching was also significantly lower from unfertilised fallow than from all other treatments (A–E, G) in the pairwise comparisons (Table 9). Due to the necessity to reduce the P load and N load in the Baltic Sea area simultaneously and in a balanced way, actions on arable land should focus on soil structure improvements rather than converting arable land to fallow. In drain water from plots with structural liming the N/P ratio was 50 but in the water from the fallow only 8 (Table 9), i.e. close to the level which can promote growth of N-fixing algae in the brackish water of Stockholm archipelago demonstrated for example by Boesch et al. (2006).

4. Conclusions

This study has demonstrated a large spatial variability in leaching of phosphorus and nitrogen, and especially particulate phosphorus (PP). Stabilisation of cracks by gyttja, especially in the deeper subsoil, and lower pH were suggested as explanatory factors for the large spatial variation. However, careful studies of soil macropore systems, including topsoil and subsoil properties, are needed to explain the unpredictability in leaching from the common type of cracking marine clay soil studied. Broadcasting or placement of fertiliser P had no clear effect on P leaching in this six-year study, and a P fertilisation at a level close to P removed by harvested crop did not result in higher P losses than when P fertilisation was completely omitted. There was a tendency (but without significant proof) for lower phosphorus losses to be measured after conventional mouldboard ploughing compared with shallow tillage, which is possibly explained by disrupting macropores. Soil not used for cultivation (unfertilised fallow) resulted in highly reduced nitrogen (N) leaching, but high PP losses were still observed. The low N/P ratio in this drainage water suggests that no tillage and no P fertilisation at all on former agricultural land is not a good solution for combating eutrophication of the nearby Baltic Sea. Instead the focus should be on mitigating macropore flow e.g. by soil structure improvements. Structural liming followed by regular ploughing in the following years should be employed for this type of soil.

Acknowledgements

Sincere thanks to Stockholm Water Co, which funded most of the experimental field equipment and to the Swedish Rural Economy and Agricultural Society for its fruitful co-operation. Special thanks to Nils-Erik Stackhammar, who managed the experiment, Johan Frank, Stockholm Water Co, who took care of equipment and water sampling, and Claudia von Brömssen at SLU for her statistical support. Grateful thanks also to the Swedish Farmers' Foundation (SLF), which funded this study, and to the Stockholm Council for Regional Growth, Environment and Regional Planning which provided initial supplementary funding.

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